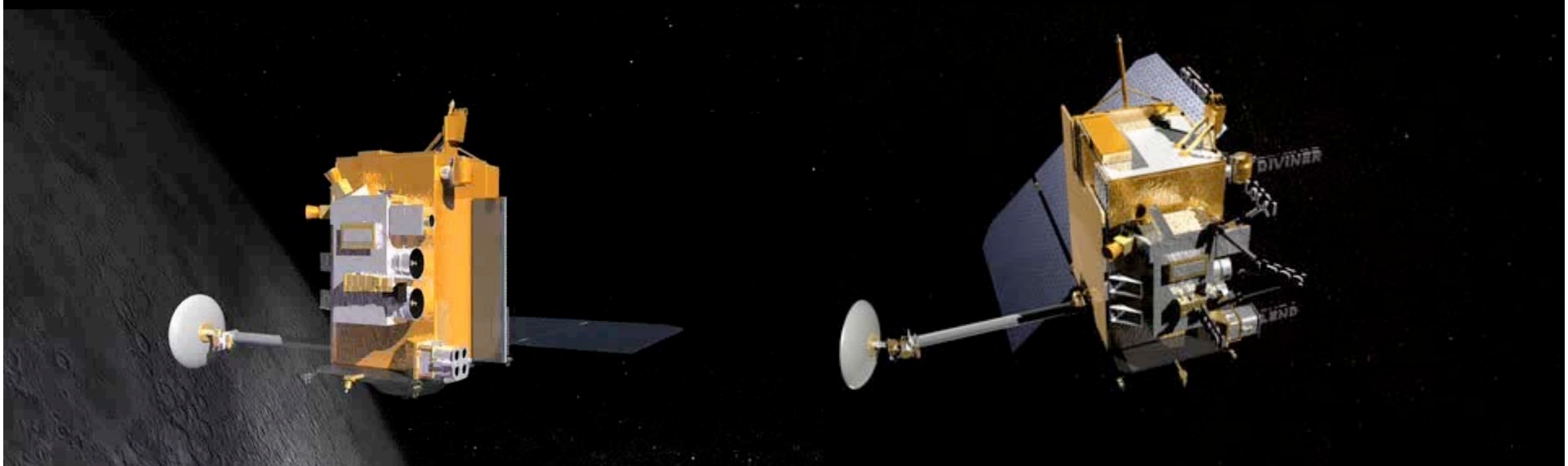
An Overview of CRaTER Results After One Year at the Moon

Harlan E. Spence

Director of the Institute for the Study of Earth, Oceans, and Space and Professor of Physics, University of New Hampshire

On Behalf of the Full CRaTER Science Team

(M. Golightly, J. Kasper, J. B. Blake, J. Mazur, L. Townsend, T. Onsager, T. Case, C-L. Huang, A. Jordan, B. Larsen, E. Semones, T. Stubbs, C. Zeitlin)



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Overview

- CRaTER ESMD Measurement Goals and Instrument Summary
- First-Year Science Highlights
  - Radiation Dose Estimates During Deep, Prolonged Solar Minimum
  - Lunar Orbit Dose Rate Comparisons with Apollo-era Estimates
  - Assessment of Variability in Galactic Cosmic Rays (GCR)
  - First Direct Measurement of >15 MeV Albedo Protons from Lunar Regolith and Comparison with Models
  - Detection of First, Weak Solar-Related Energetic Particle Event of New Solar Cycle
- What's Next? A tale of two Directorates: ESMD → SMD
- Summary

ESMD Measurement Goals

To characterize the global lunar radiation environment and its biological impacts

- Six-element, solid-state detector and tissue-equivalent plastic (TEP) telescope

- Sensitive to cosmic ray particles with energies greater than ~10 MeV, primarily protons, but also heavy ions, electrons, and neutrons
    - *Galactic cosmic rays – GCRs*
    - *Solar energetic particles– SEPs*

- Measure spectrum of Linear Energy Transfer (LET = energy per unit path length deposited by cosmic rays as they pass through or stop in matter) behind different amounts of TEP

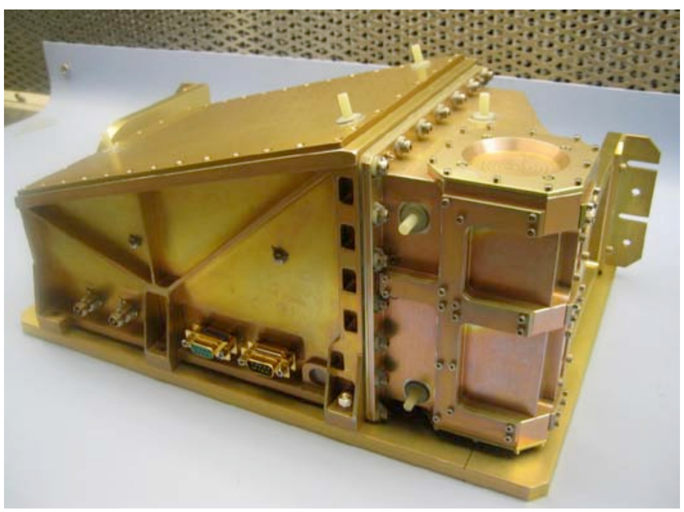
- Accurate LET spectrum is missing link needed to constrain radiation transport models and radiation biology to aid safe exploration

CRaTER Instrument Summary

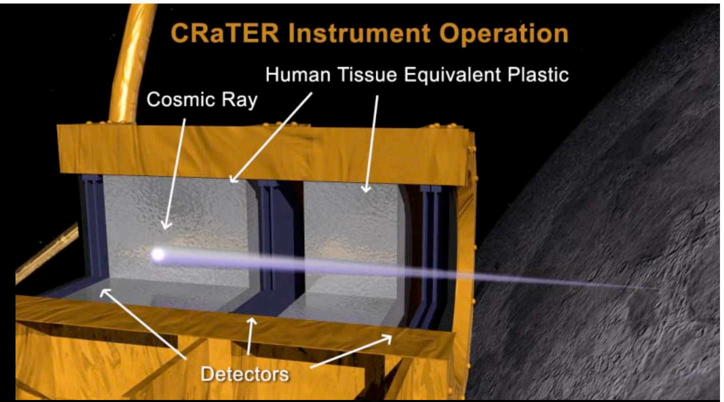
Cosmic Ray Telescope for the Effects of Radiation (CRaTER) Investigation

(Spence et al., SSR, 2010)

"Luna Ut Nos Animalia Tueri Experiri Possimus"
("In order that we might be able to protect and make trial of living things on the Moon")

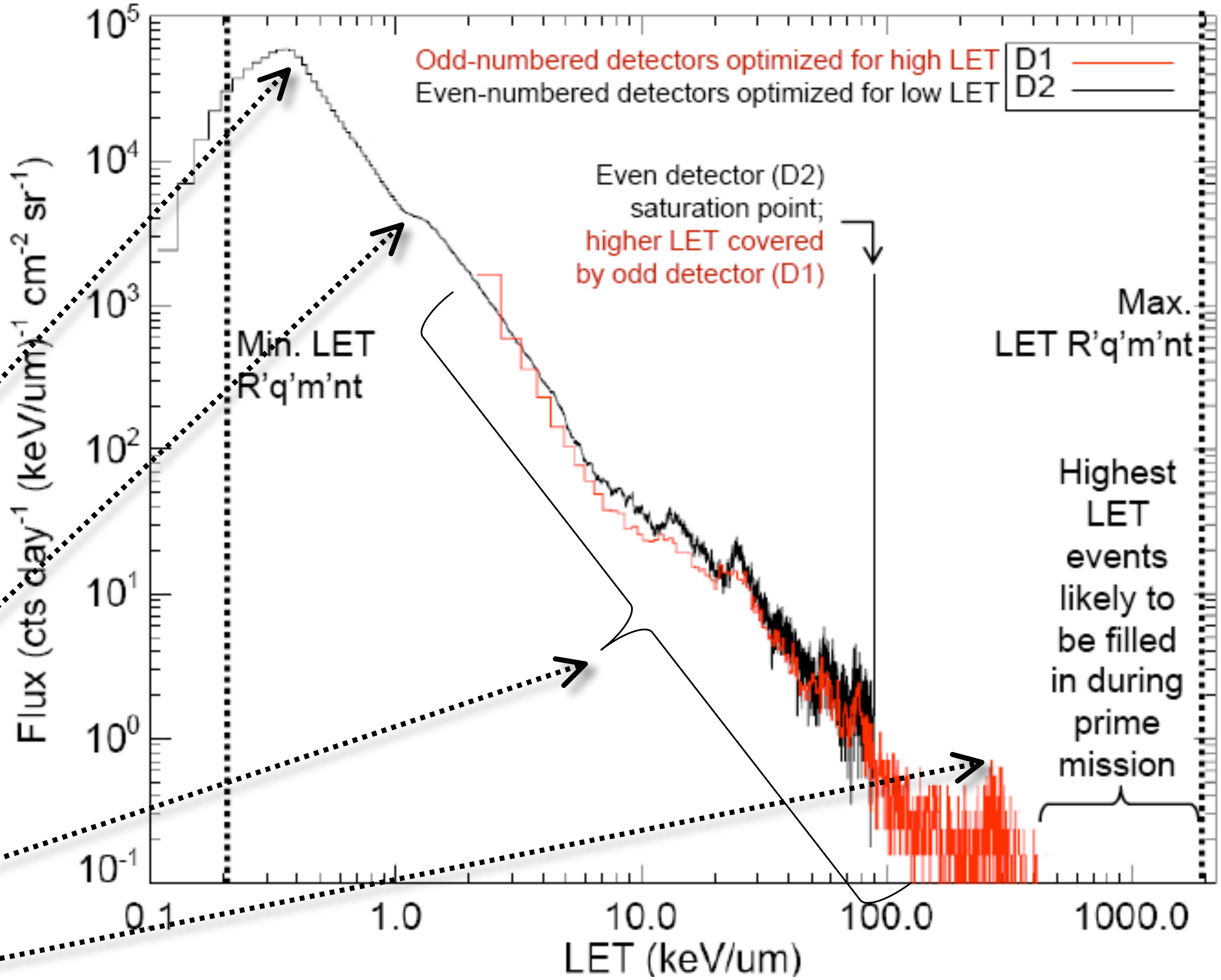


CRaTER Concept of Operations



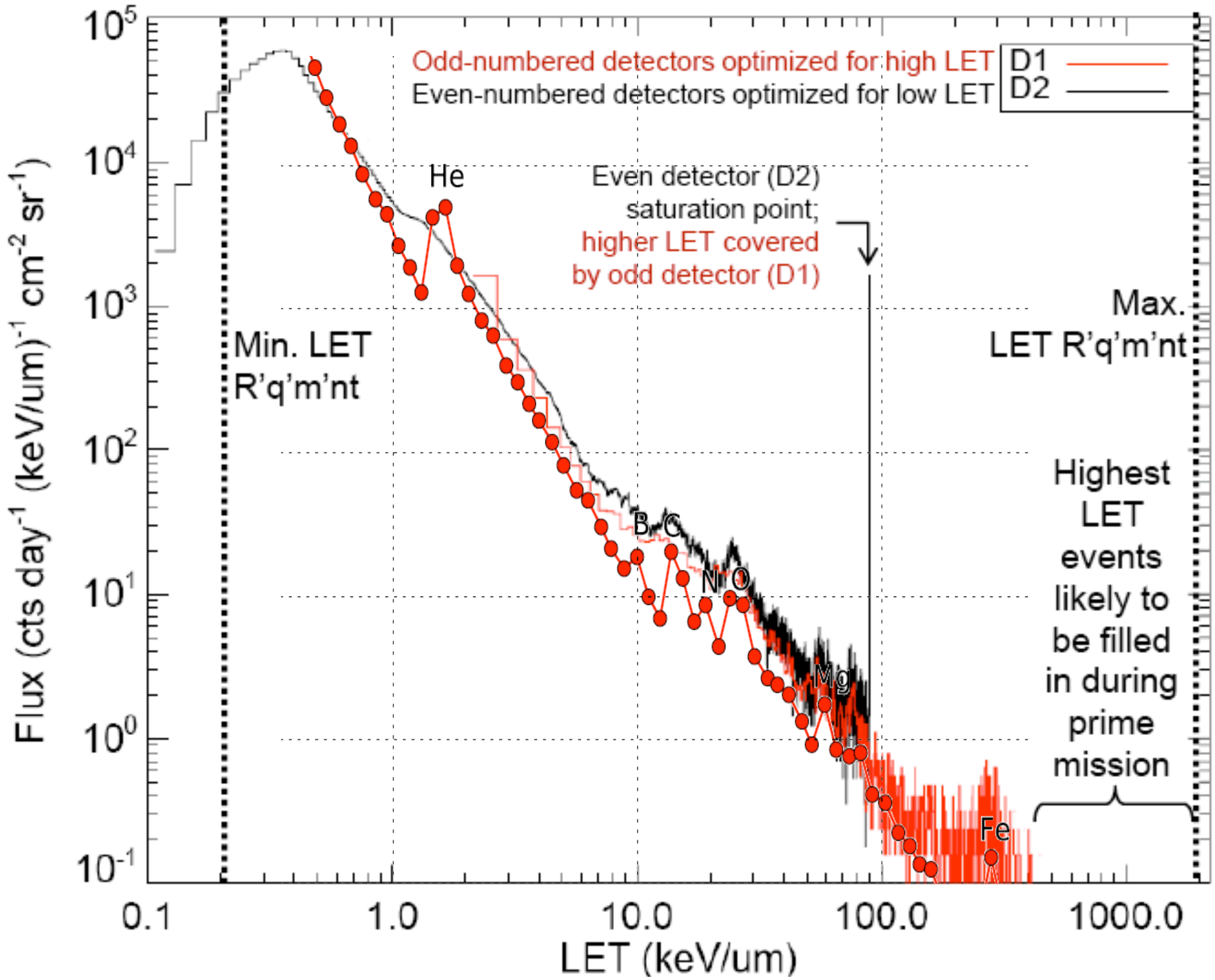
1st-Year Highlight: GCR LET Spectra

- **Composite D1, D2 LET spectra at zenith entrance constructed from 2-4-6 coincident events**
- **Protons contribute most to peak at ~0.4 keV/μm**
- **Helium ions emerge in spectrum at ~1 keV/μm**
- **All heavier ions out to iron peak at ~300 keV/μm**

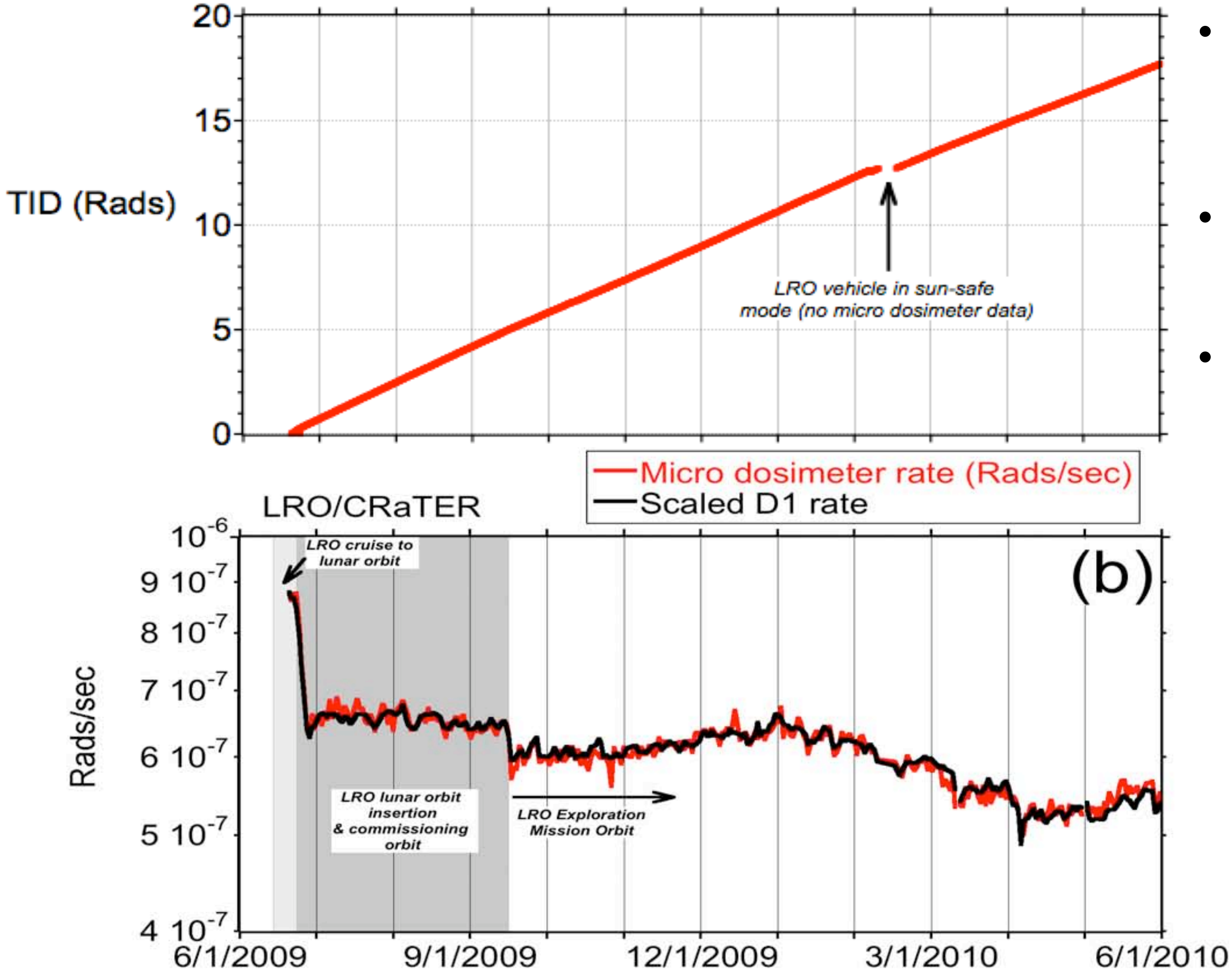


Measured vs. Modeled GCR LET Comparison During Solar Minimum

- Compare CRaTER LET spectrum to comparable model predictions
- Use CREME86 model with GCR flux from prior solar minimum conditions (1996)
- Compute LET in silicon behind 1mm of aluminum (similar thickness to CRaTER's zenith endcap)
- Ion peaks well aligned
- LET flux **higher than last solar cycle**



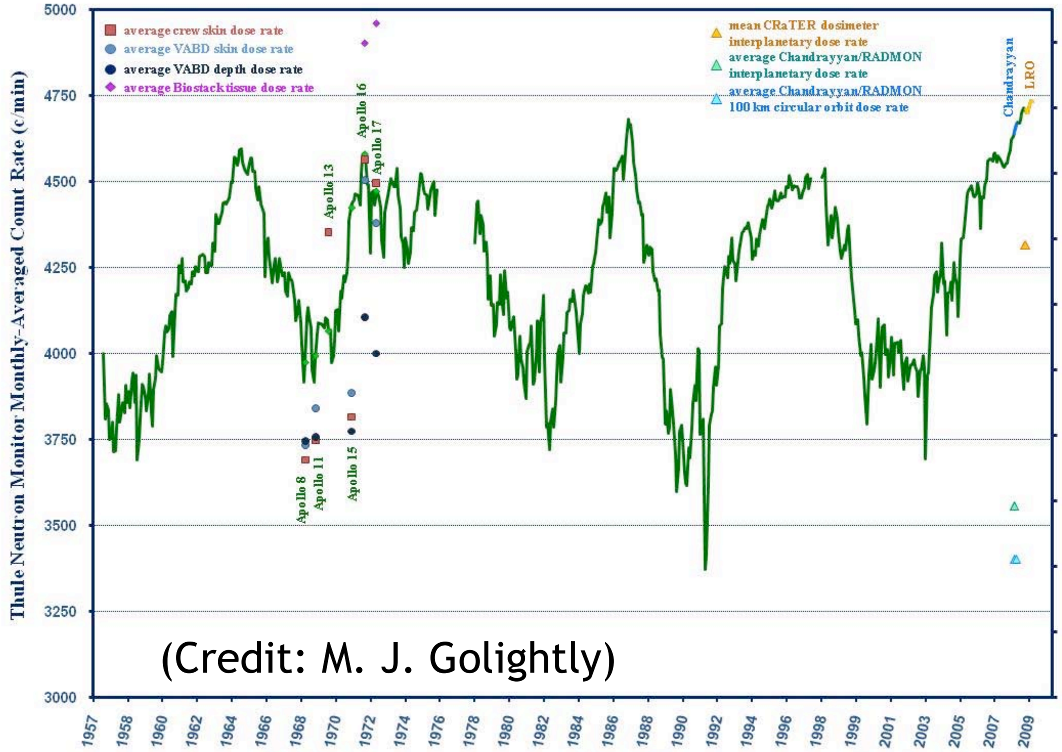
Radiation Dose and Dose Rate During Deep, Prolonged Solar Minimum



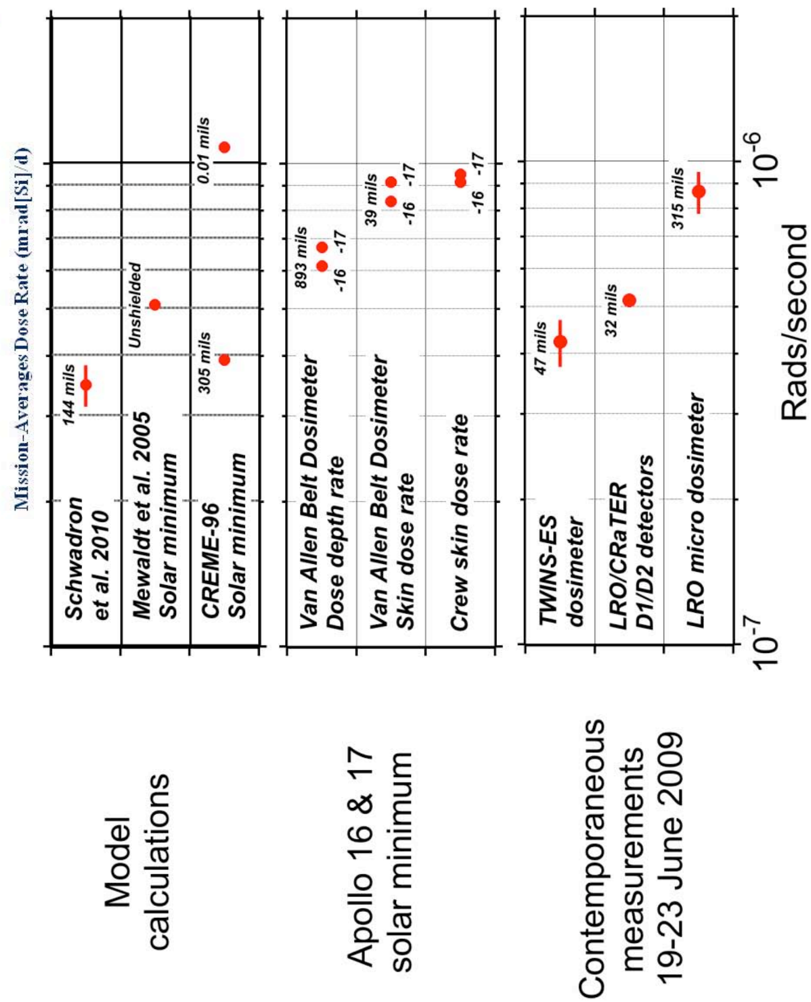
- Total ionizing dose (TID) in silicon for 1-year ESMD mission ~18 Rads
- Typical mission dose rate ~0.6 μRads/sec
- Dose rate variations:
  - Highest during cruise phase in deep space
  - Lower during commissioning phase
  - Variations since 9/09 track solar cycle
  - GCR peak in ~Jan 2010; dropping steadily while coming out of solar minimum

(Credit J. Mazur)

Lunar Orbit Dose Rate Comparisons with Apollo-era Estimates

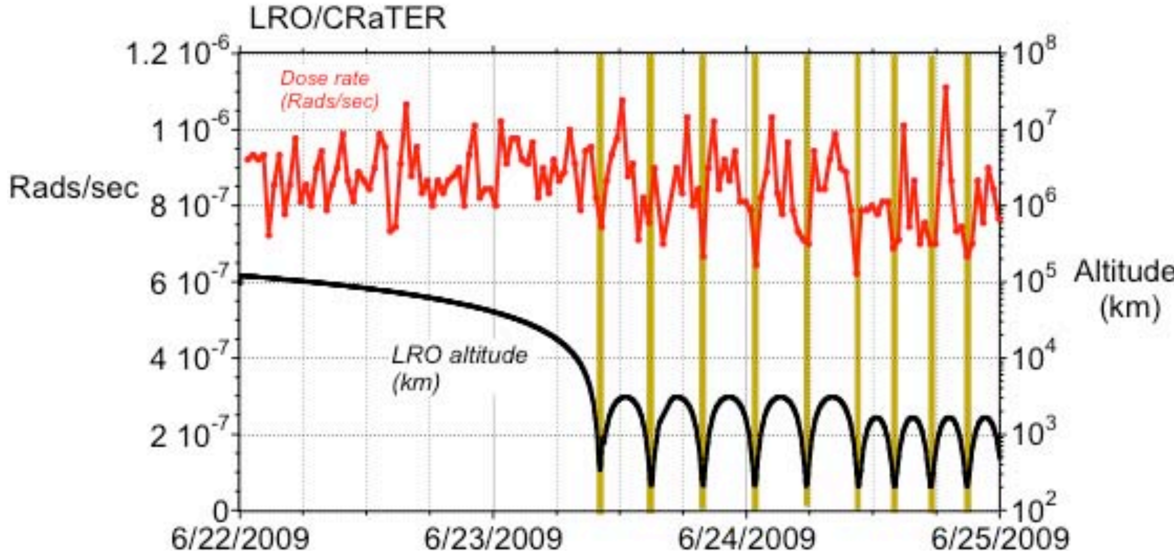


(Credit: J. Mazur)

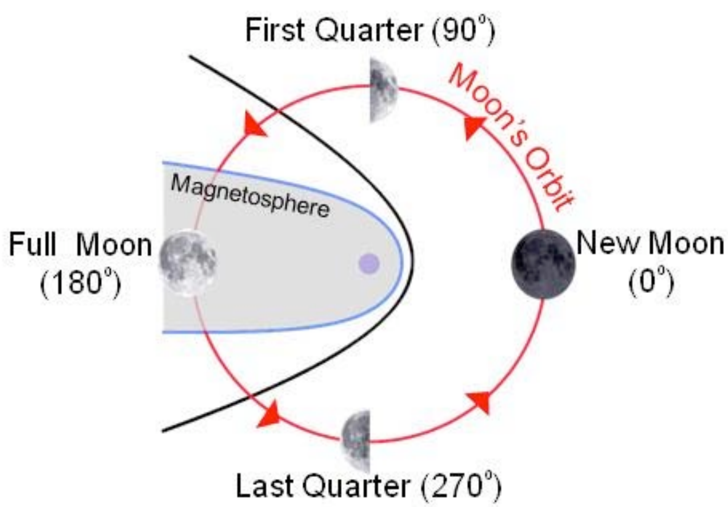


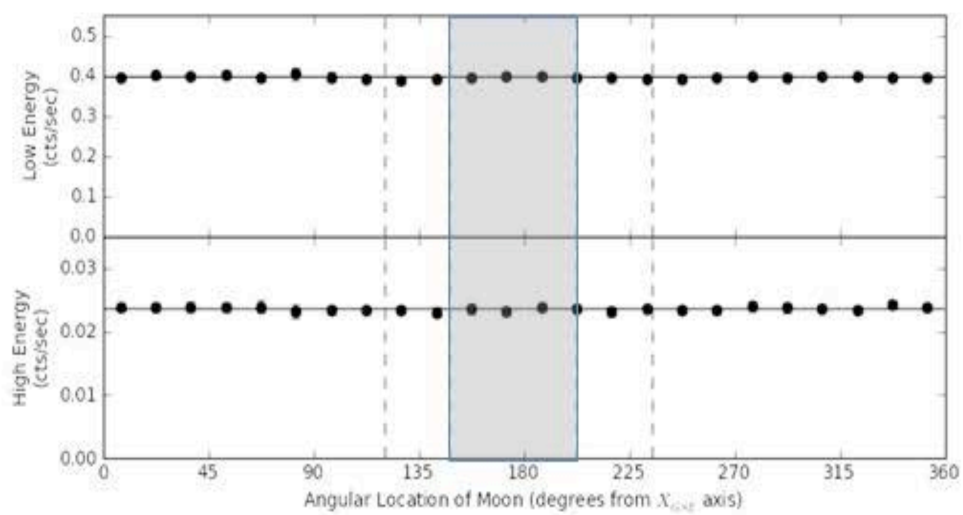
- LRO dose rates compare favorably with Apollo-era estimates, however factor of 3 between contemporaneous measurements, models, and solar cycle differences require reconciliation

Assessment of Sources of Variability in Galactic Cosmic Rays (GCR) at Moon

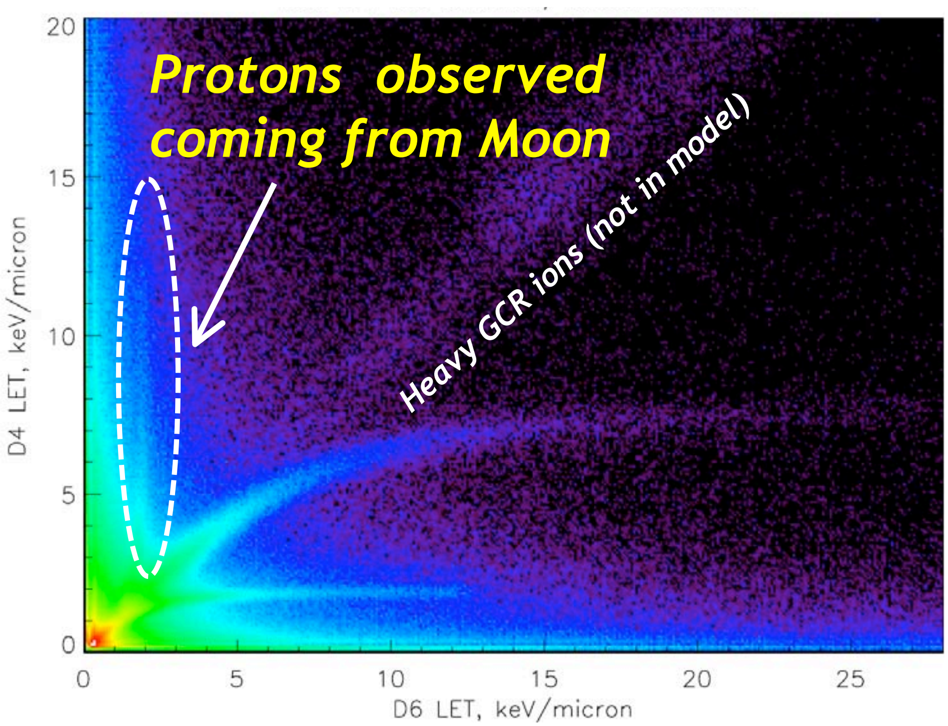


- Altitude dependent dose rate consequence of Moon blocking more or less of the primary GCR (J. Mazur)
- CRaTER confirms that Earth's distant magnetosphere provides no measurable shielding from GCR (T. Case)

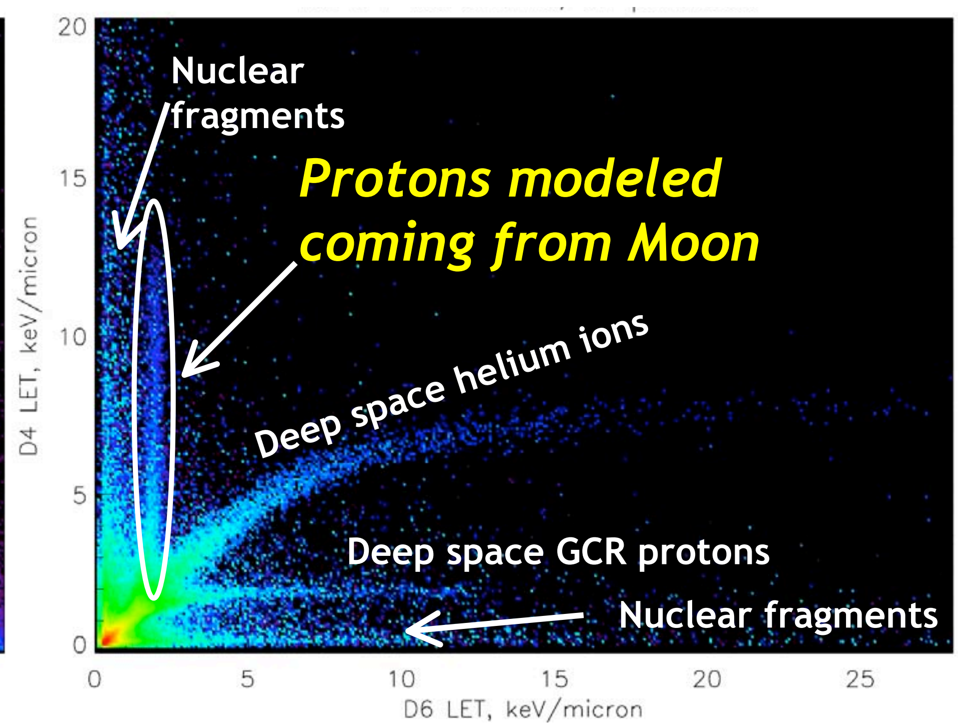




First Direct Measurement of >15 MeV Albedo Protons from Lunar Regolith



CRaTER GCR Observations

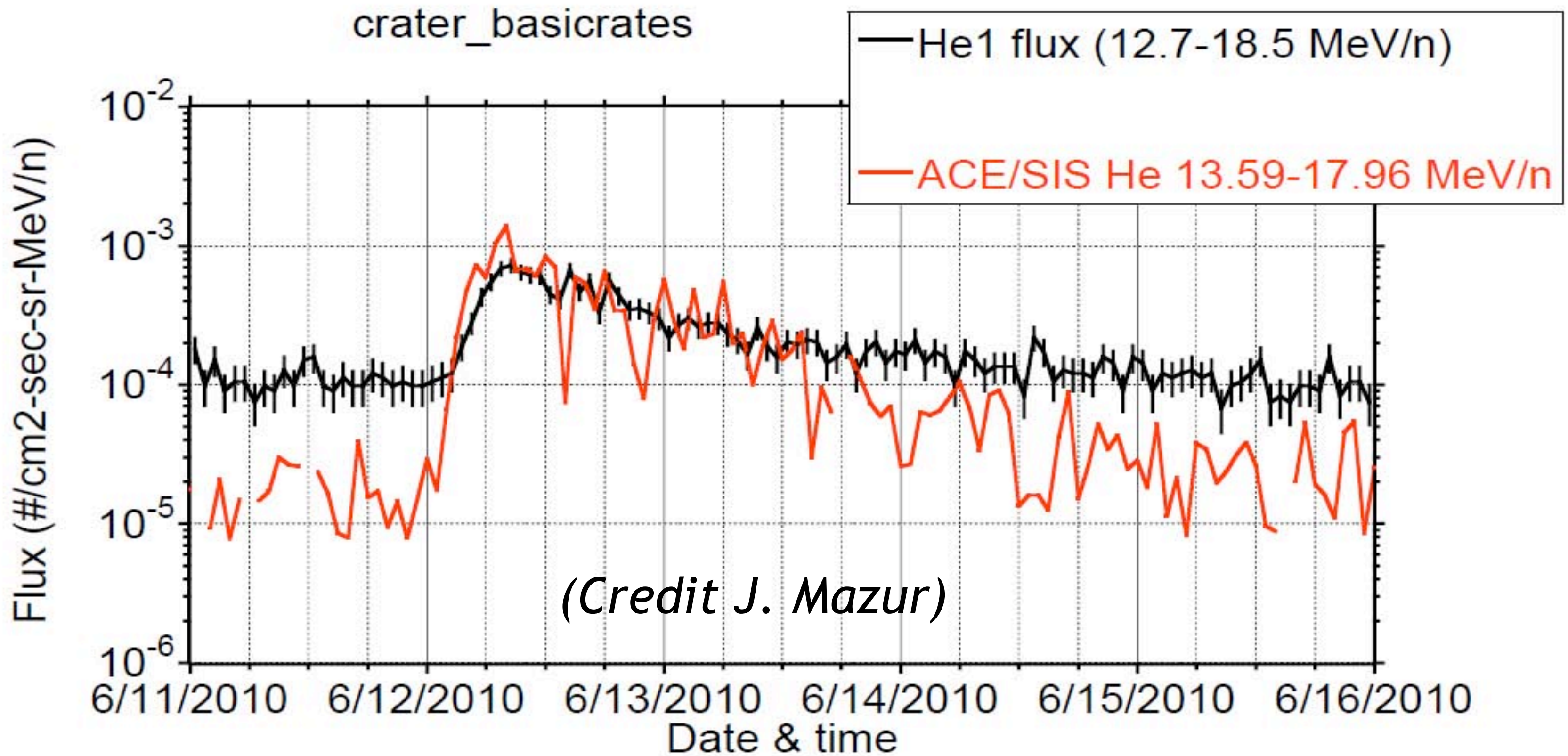


CRaTER Model Response to GCR

- **CRaTER confirms existence of lunar proton albedo (adds to well-known neutron albedo)**
- Upward-moving lunar protons (albedo) created from primary GCR slamming into the Moon
- Nuclear fragments (mostly pions, kaons, etc.) generated as GCR interacts with tissue-equivalent plastic within CRaTER – a major motivation for this experiment!
- Heavy GCR ions (not included in model) seen clearly in observations out to Iron

(Credit M. Looper)

Detection of First, Weak Solar-Related Energetic Particle Event of New Cycle



- CRaTER detection of weak event includes alpha particles with high-energy-spectral resolution; comparison with ACE observations underway and favorable

- Strong detection by CRaTER despite unremarkable event promises greater science opportunities as Sun wakes up…

What's Next? A Tale of Two Directorates

- SMD "adopts" LRO from ESMD on 9/16/2010, one year following launch for a "new" two-year science mission

- Though designed for "Exploration Enabling Measurements" CRaTER instrument capabilities allow for science studies aligned with:
  - NRC Decadal Survey (2003)
  - NRC Scientific Context for Exploration of the Moon report (2007)

- SMD CRaTER science thrusts include:
  - Characterizing changing lunar radiation environment on variety of time scales during rise from solar minimum
  - Mapping surface proton albedo variability to explore surface interactions of space environment with regolith

Summary

- CRaTER in excellent health after one year at the Moon and generating discoveries during ESMD phase
  - Outstanding measurements of LET spectra at Moon reveal known features (e.g., peaks from heavy ions) as well as surprises (e.g., high fluxes compared to pre-launch expectations)
  - While at a space-age high, GCR radiation environment is workable challenge for short missions to Moon but remains major concern for long missions well beyond LEO
  - Lunar GCR flux (and radiation dose) reduced compared to deep space because of proximity to absorbing Moon, however, Earth's magnetotail provides no shelter from >15 MeV GCR (i.e., at energies of biological relevance)
  - First detection of proton albedo from lunar regolith compares well with simulations
  - Strong detection of first, weak solar particle event demonstrates SMD promise for studies of this phenomenon virtually absent during ESMD phase

Backup Slides

CRaTER Performance Specifications

CRaTER's design has thick/thin detector pairs at 3 points through TEP:

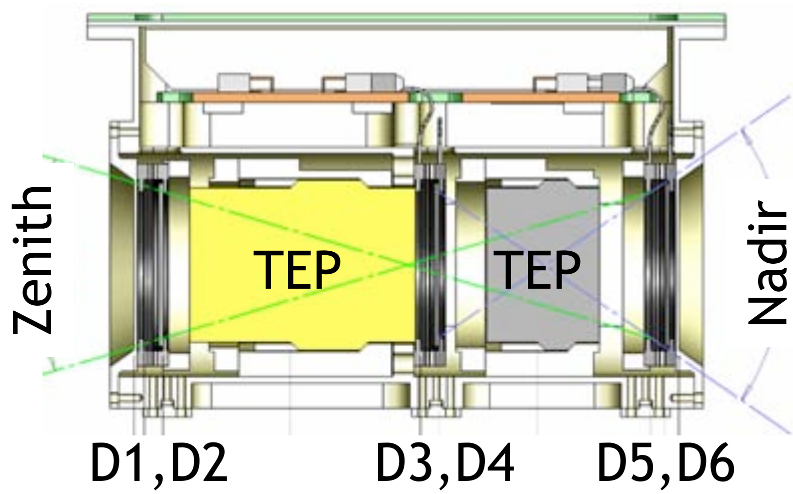
- 3 "low LET" thick detectors (D2,D4,D6)- 200 keV to 100 MeV
- 3 "high LET" thin detectors (D1,D3,D5) - 2 MeV to >300 MeV

nergy resolution <0.5% (at max energy); GF ~1 cm^2-sr (typical)

This corresponds to:

ET from **0.2 keV/µ to 2 MeV/ µ**

xcellent spectral overlap in the **100 kev/µ** range (key range for RBEs)



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